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Methods and geophysical attributes for the Fisheries Risk Assessment Tool

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

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ABSTRACT

Development of the Fisheries Risk Assessment Tool (FRAT) was carried out by BGC Engineering Inc. (BGC) and Fisheries and Oceans Canada (DFO) between 2005 and 2010. The objective of the FRAT was to explore methods to facilitate a prioritization of pipeline stream crossing applications on the proposed Mackenzie Gas Project according to an overall risk rating, thereby providing an objective means for allocating review effort and improving the timely review of development applications. The hazards considered in the FRAT were limited to the potential for stream sedimentation under natural conditions and during and following pipeline construction activities. The consequences considered in the FRAT were limited to potential localized impacts to fish and fish habitat as a result of stream sedimentation.

Additionally, it was believed that the FRAT could facilitate the storage and retrieval of relevant terrain, watercourse and fisheries data for each proposed pipeline crossing, improve communication between DFO and the proponent, and encourage the use of best practices for pipeline routing, design, construction, and operation. While the focus of the FRAT was the Mackenzie Gas Project, it was hoped that ultimately a modified version of the FRAT could be applied across Canada to streamline DFO's regulatory process for other pipeline watercourse crossings.

Méthodes et caractéristiques géophysiques utilisés pour l'outil d'évaluation des risques liés aux pêches

RÉSUMÉ

BGC Engineering Inc. (BGC) et Pêches et Océans Canada (MPO) ont élaboré l'outil d'évaluation des risques liés aux pêches entre 2005 et 2010. L'objectif de cet outil était d'étudier des méthodes permettant de faciliter la priorisation des demandes de franchissement des cours d'eau par le gazoduc dans le cadre du projet gazier Mackenzie proposé en fonction d'une évaluation du risque global, ce qui fournirait un moyen objectif de déterminer les efforts à consacrer aux examens et d'améliorer l'examen opportun des demandes d'aménagement. Les dangers pris en compte dans l'outil se limitaient au risque de sédimentation des cours d'eau dans des conditions naturelles, ainsi que pendant et après la construction du gazoduc. Les conséquences prises en compte dans l'outil se limitaient aux impacts localisés potentiels sur le poisson et l'habitat du poisson, résultant de la sédimentation des cours d'eau.

En outre, on pensait que l'outil d'évaluation des risques liés aux pêches permettrait de faciliter le stockage et l'extraction des données pertinentes sur les terrains, les cours d'eau et les pêches pour chaque franchissement de cours d'eau proposé, d'améliorer les communications entre le MPO et le promoteur, et d'encourager l'application de meilleures pratiques pour le tracé, la conception, la construction et l'exploitation du gazoduc. Même si l'outil était axé sur le projet gazier Mackenzie, on espérait en fin de compte être en mesure d'en appliquer une version modifiée dans tout le Canada afin de rationaliser le processus réglementaire du MPO pour d'autres traversées de cours d'eau par des gazoducs.

INTRODUCTION

BGC Engineering Inc. (BGC) was retained by Fisheries and Oceans Canada (DFO) to prepare a research document on the attributes and weighting to determine sediment hazard in the Fisheries Risk Assessment Tool (FRAT), and a description of how sediment hazard and fish consequence are combined in the FRAT to arrive at qualitative risk estimates. This document comprises four main sections:

- background information on the objectives and development of the FRAT;
- review of risk assessment methods and rationale for the methods used to combine sediment hazard and fish consequence within the FRAT to arrive at estimates of risk;
- additional description of the rationale for the selection and numerical values assigned to geophysical attributes used in the sediment hazard ratings; and
- opportunities to further improve the FRAT.

BACKGROUND

The impetus for the development of the Fisheries Risk Assessment Tool (FRAT) was the proposed Mackenzie Gas Project (MGP) which called for the development of gas production fields and buried gathering pipelines in the Mackenzie Delta, a buried natural gas liquids (NGL) pipeline between Inuvik and Norman Wells, and a buried gas pipeline along the Mackenzie Valley to a location in Alberta where it would connect with the existing Alberta system. The proposed pipeline routes crossed 643 identified streams. Most were vegetated channels where open cut construction was proposed by the Proponent, but many would require some form of isolation techniques. Horizontal directional drilling (HDD) methods were proposed at several large rivers. The presence of continuous and discontinuous permafrost along the pipeline routes was a complicating factor for which there is very limited experience in the Canadian pipeline industry.

In anticipation of the increased regulatory workload associated with the Project, DFO wanted a tool to optimize and streamline the process of pipeline stream crossing application review and, later, construction and operations inspection requirements.

Work on the FRAT began in 2005 with the development of a geophysical database that characterized physical attributes of river valleys and channels in the vicinity of proposed pipeline watercourse crossings, plus a DFO database that characterized the fisheries resources and habitat at each crossing. The data incorporated in these initial databases were provided by DFO.

Preliminary algorithms were developed to estimate the sedimentation hazard likelihood from landslides and bank erosion, and the fisheries resource sensitivity (or fish consequence) using the available data. These were coupled in a qualitative risk matrix that assigned an overall risk rating to each stream crossing by considering both sedimentation potential and likelihood of consequences to fisheries resources. It was postulated that the overall risk rating could be used to help determine the required level of regulatory review and the appropriate authorization process carried out by DFO under the *Fisheries Act*. DFO, as described in the Canadian Association of Petroleum Producers Pipeline Associated Watercourse Crossings guidelines (CAPP 2005) was already contemplating similar approaches to guide the selection of pipeline watercourse crossing methods and management approaches.

In 2008 and 2009, BGC was retained by DFO to expand the FRAT to consider a broader range of geohazard types and three sedimentation scenarios including baseline conditions, pipeline construction, and pipeline operation and maintenance. At the same time, Environmental Dynamics Inc. (EDI) was retained by DFO to advance the development of the fish consequence model. The main objective of the FRAT refinements was to facilitate a prioritization of pipeline stream crossing applications according to an overall risk rating, thereby providing an objective means for allocating review effort and improving the timely review of development applications. Additionally, it was believed that the FRAT could facilitate the storage and retrieval of relevant terrain, watercourse and fisheries data for each proposed pipeline crossing, improve communication between DFO and the proponent, and encourage the use of best practices for pipeline routing, design, construction, and operation. While the focus of the FRAT was the Mackenzie Valley, it was hoped that ultimately the FRAT could be applied across Canada to streamline DFO's regulatory process for other pipeline watercourse crossings.

To meet these objectives an efficient set of algorithms was required to rank the potential sedimentation hazards and risks at several hundred pipeline stream crossings of varying size and complexity using data that are likely to be available at the end of the pipeline front-end engineering design (FEED) phase. Available data sources were anticipated to include aerial photography, satellite imagery, 1:50,000 scale topography, bedrock geology and surficial geology maps, baseline geotechnical, hydrotechnical and environmental surveys, and basic engineering designs for each proposed stream crossing. Only generic designs are typically available for small and medium-sized stream crossings at this design phase. Key attributes extracted from these datasets were stored in the FRAT databases and used to generate the risk rankings.

As part of the 2008 and 2009 FRAT refinements, preliminary algorithms were developed to estimate the annual sediment volume that is mobilized and enters a stream as a result of the following hazards and scenarios:

- Bank Erosion (baseline conditions, pipeline construction, pipeline operation)
- Shallow Landslides (baseline conditions, pipeline construction, pipeline operation)
- Right of Way Surface Erosion (baseline conditions, pipeline construction, pipeline operation)
- Site Grading (pipeline construction)
- Trench Excavation and Backfilling (pipeline construction)

The sedimentation hazard under baseline conditions refers to the likely volume of sediment from the stream banks and approach slopes that naturally enters the stream course at the location of the proposed pipeline crossing. The pipeline construction scenario involves the construction and cleanup periods (which will typically occur during the winter) and the following spring freshet when much of the construction-related sediment is most likely to be mobilized. Pipeline operation refers to residual sedimentation hazard following construction. Two different operating scenarios were considered:

- Gas temperature warmer than ambient (which may contribute to thaw settlement if the pipeline passes through ice-rich permafrost) and
- Gas temperature cooler than ambient (which may contribute to frost heave and frost bulb formation if the pipeline passes through a talik or unfrozen zone).

For each hazard type and each scenario, an estimate of the average volume of sediment mobilized on an annual basis was made using a standard set of queries related to site attributes and anticipated construction and site restoration procedures. The likelihood that the mobilized

sediment enters the stream (referred to as the spatial probability of impact) was also assigned as a function of hazard type, proximity of the hazard to the stream, and other attributes such as the presence of natural or artificial barriers.

Estimated sediment volumes mobilized and entering a stream were summed for the hazards applicable to each scenario and combined with a fisheries sensitivity (consequence) ranking to assign risk rankings to each stream crossing using a qualitative matrix like that shown in Table 1.

If desired, the estimated sedimentation volume score for baseline conditions could be subtracted from the volume estimates for construction and operation to evaluate the incremental impact of these activities on sedimentation volume and fisheries risk.

Data necessary to calibrate the algorithms and attribute scores used to estimate sedimentation volume are not available and, consequently, the volume estimates are not expected to be precise. The volume estimates are intended to be used as a basis for relative ranking only, and for this reason are more appropriately referred to as 'Volume Scores'. Over time there may be opportunities to calibrate the algorithms so that predicted Volume Scores more closely correlate to measured or estimated sediment volumes or turbidity levels.

Table 1. Sample Qualitative FRAT Risk Matrix for a Proposed Pipeline Stream Crossing

Annual Sedimentation Volume Score	Fisheries Sedimentation Consequence[1]				
	Significant (> 2000)	Major (1400-2000)	Medium (599-1399)	Minor (50-599)	Insignificant (< 50)
Very Significant (> 1000)	VH	VH	H	M-H	M
Significant (500-1000)	VH	H	M-H	M	M
Major (100-500)	H	M-H	M	M	L-M
Medium (50-100)	M-H	M	M	L-M	L
Minor (10-50)	M	M	L-M	L	VL
Insignificant (< 10)	M	L-M	L	VL	VL

[1] See Table 3 for an explanation of the numerical scores.

Algorithms were not developed to address all conceivable means of stream sedimentation around pipeline crossings of fish habitat, nor did they address other construction-related hazards such as fuel spills. The intent was to focus on a manageable number of hazards and construction/operation scenarios to capture the key factors that will contribute to a departure from baseline sedimentation potential during and following pipeline construction.

Database population of geophysical attributes, sensitivity analyses, and preparation of a draft user's manual were carried out by BGC in 2009 and 2010.

In summary, the sedimentation algorithms and associated data requirements that were developed for the FRAT were intended to:

1. Highlight the key attributes contributing to each type of sedimentation hazard.

2. Facilitate the assignment of a relative hazard and risk ranking for each proposed stream crossing so that regulatory review effort could be prioritized.
3. Encourage the application of best practices to mitigate these hazards and risks, such as those specified in the CAPP guidelines (CAPP 2005).

The philosophy behind the development of the FRAT aligns well with generally accepted practices for risk management. Quantification of risk is only a small part of risk management, and much of the value lies in the process of identifying hazards, potential consequences, and options and costs for mitigation, communication and consultation with stakeholders, and prioritization of management and mitigation efforts within a logical framework.

Ongoing review of the FRAT has been carried out by DFO and representatives from the Canadian pipeline industry. In the process, several very valid questions have been raised, generally along the lines of:

- What is the basis for using a qualitative risk matrix to estimate fisheries risk?
- What is the logic behind the selection and weighting of the geophysical attributes used in the FRAT stream sedimentation model?
- What is the uncertainty associated with the FRAT risk estimates?
- What is the rationale and logic behind the selection and weighting of the biological attributes used in the FRAT?

Partial answers to many of these questions can be found in Rempel and Porter (2008), and the various internal memoranda and technical reports prepared by BGC and EDI between 2007 and 2010 for DFO and Aboriginal Affairs and Northern Development Canada (AANDC) during the process of the FRAT development. The purpose of this research document is to help pull this information into a single report, to provide some additional insight and clarification, and to highlight some areas where further improvements could be made.

RATIONALE FOR A RISK MATRIX APPROACH

This section of the report describes techniques that are available to develop an inventory and ranking of risks for the purposes of decision making, and the rationale for adopting a qualitative risk matrix approach for the FRAT.

DEFINITIONS

The FRAT makes use of several terms that are defined as follows:

Hazard – A condition with the potential for causing an undesirable consequence.

Probability – The annual likelihood of a specific outcome. Probability is expressed as a number between 0 and 1, with 0 indicating an impossible outcome, and 1 indicating that an outcome is certain in a given year.

Consequence – The outcomes or potential outcomes arising from the occurrence of a hazard, expressed qualitatively or quantitatively, in terms of loss, damage, injury or loss of life.

Risk – A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often quantified through the numerical product of Probability x Consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

The FRAT is intended to address the risk of sediment being mobilized at the location of a pipeline stream crossing, entering a stream, and having a negative impact on fishes. In product form, the equation for risk for any given mode of stream sedimentation could be expanded as follows:

[1] $Risk = P(H) \times P(S{:}H) \times P(T{:}S) \times V \times E$

where,

- P(H) = probability of a hazard of a specific magnitude occurring in a specific location (e.g., surface erosion causing the mobilization of sediment from a slope).
- P(S:H) = the probability of spatial impact (e.g., the likelihood that sediment mobilized from a slope enters a watercourse and the location of fish habitat, although the potential for downstream impacts to habitat could also be incorporated at a later date using this factor).
- P(T:S) = the probability of temporal impact (e.g., the temporal probability that fish or fish habitat is present when the sedimentation event occurs. Currently this is assigned a value of 1.0 within the FRAT, implying that fish and/or fish habitat are always present and do not vary temporally. This is an assumption that should be examined further and perhaps modified in a future version of the FRAT).
- V = the vulnerability of the fish habitat expressed as the proportion of damage (i.e., 0 no damage) to 1 (complete loss of habitat) if sediment impacts the habitat.
- E = the value of the elements at risk (in this case, the value of the fish habitat).

RISK ESTIMATION OPTIONS

Three options for estimating and ranking risk include:

1. Semi-quantitative risk indexing
2. Quantitative risk assessment
3. Qualitative risk matrices

Semi-quantitative risk indexing offers a method to generate a relative ranking of risks. Factors that influence the probability and consequence of a potential hazard are assigned numerical values and mathematically combined. Communication of the methodology and results is relatively straight-forward, but challenges often arise when attempts are made to compare risks from multiple hazard types using semi-quantitative methods.

Quantitative risk assessment sits at the other end of the spectrum. Hazard probability, temporal and spatial probability, and vulnerability are assigned numerical values between 0 and 1 using a combination of historical data, numerical models and professional judgement. These are combined in product form, along with a quantitative estimate of the value of the elements at risk, to arrive at a numerical estimate of risk. For geohazard assessment, risk estimates are typically reported in terms of dollars per year (for measures of economic risk) or annual probability of life loss (for measures of life safety risk). Quantitative risk assessment can readily highlight differences in risks that may span several orders of magnitude, and can be used to compare and/or sum up risks from multiple hazard types. One of the challenges with quantitative risk assessment is that not all consequences are easily quantifiable in economic or life safety terms. Another common challenge is in assigning reliable estimates of event probabilities where data for model calibration are sparse.

Qualitative risk matrices can take advantage of some of the strengths of semi-quantitative indexing and quantitative risk assessment methods while mitigating some of their weaknesses. In a risk matrix such as that illustrated in Table 1, a measure of hazard is usually represented along the vertical axis, a measure of consequence is presented along the horizontal axis, and the combination of the two parameters captured within the body of the matrix is a measure of risk. Often qualitative terms are used to describe different levels of hazard, consequence, and risk, although these are usually supported by underlying quantitative or semi-quantitative estimates. Measures of hazard and/or consequence can span orders of magnitude, if required, but the use of qualitative terms helps to avoid the illusion of precision commonly associated with quantitative methods. While the underlying models used to assign parameter values may be complex, the risk matrix approach is usually straightforward to communicate. Different management protocols and timeframes for action can be assigned to different risk levels. The matrices are usually set up such that 'Moderate' risks are within a range that may or may not be tolerable for the organization, and that require further assessment. 'High' and 'Very High' risks usually exceed an organization's tolerance criteria and are prioritized for risk control. 'Low' and 'Very Low' risks are usually tolerable, though may require ongoing review.

THE FRAT RISK MATRIX

Both the Annual Sedimentation Volume and Fisheries Sedimentation Consequence scores are estimated using semi-quantitative methods. As illustrated in Table 1, the qualitative FRAT risk matrix combines estimates of sediment volume and fish consequence to arrive at a risk rating.

Three risk ratings are estimated for each proposed pipeline crossing: sedimentation risk under natural conditions, during and immediately following pipeline construction, and under long-term pipeline operating conditions.

Table 2 illustrates the range of hazards considered in the FRAT for each scenario.

Table 2. Sedimentation hazards contributing to the Annual Sedimentation Volume Score

Scenario/Hazard	**Bank Erosion**	**Surface Erosion**	**Shallow Slope Instability**	**Slope Grading Spoil Management**	**Trenching Spoil Management**
Baseline	√	√	√	**X**	**X**
Construction and 1st Freshet	√	√	√	√	√
Operations a) Cold Gas b) Warm Gas	√	√	√	**?**	**X**

The Annual Sedimentation Volume Score is an estimate of total volume of sediment mobilized from the approach slopes, banks and channel of each stream crossing that enters the stream. The volume score is dimensionless, but it is based on sediment volume estimates in cubic metres. For example, a 'Medium (50-100)' volume score implies that the estimated annual volume of sediment mobilized from the pipeline right of way approach slopes, bank and stream channel, and entering the stream, is between 50 and 100 m^3.

As shown in Table 3, the Fisheries Sedimentation Consequence considers several factors including the fish species that are present and their sensitivity, the presence of critical habitats that are used for spawning or overwintering, and the sensitivity of the habitat to an increase in stream sedimentation. Attributes associated with each of these factors are assigned numerical scores that are combined using an algorithm to arrive at the Fisheries Sedimentation Consequence for each stream crossing. A detailed description of the attributes and rationale for determination of the Fisheries Sedimentation Consequence score is provided in an internal report prepared for DFO by EDI in 2009. It is expected that the selection and weighting of the factors considered in the consequence model will require further review by DFO fish biologists.

Table 3. Fisheries Sedimentation Consequence (EDI unpubl. rep.).

Consequence Rating	Numerical Score	Qualitative Description and Typical Scenario
Significant	>2000	Three or more Class 'A' sensitive species present. Low* species diversity. Reach contains critical habitats used for spawning or over-wintering. Habitat is very sensitive.
Major	1400-2000	Class 'A' sensitive species present. Low to moderate species diversity. Reach contains critical habitats used for spawning or over-wintering. Habitat is sensitive.
Medium	599-1399	No Class 'A' sensitive species present. Moderate species diversity. Reach may contain critical habitats used for spawning or over-wintering. Habitat is moderately sensitive.
Minor	50-599	No Class 'A' sensitive species present. Moderate to high species diversity. Reach does not contain critical habitats used for spawning or over-wintering. Habitat is marginally sensitive.
Insignificant	<50	No sensitive species present. High* species diversity or no fish present. Reach does not contain critical habitats used for spawning or over-wintering. Habitat is not sensitive

*the rationale for assigning either a high or low consequence score for "fish diversity" is still unclear. In the original fish consequence model, Environmental Dynamics Incorporated (EDI) assigned a high consequence score for crossings with high fish diversity; however this was reversed in a revised model. The attribute "species diversity" requires further discussion.

A qualitative risk matrix was chosen as a means of combining the volume and consequence scores into a risk rating. Given the uncertainties associated with several of the numerical parameters used in the volume score, and the qualitative nature of the consequence score, a purely quantitative approach would not be appropriate.

Ideally, the parameter scores used along each axis of a qualitative risk matrix span, increase by an order of magnitude from one category to the next. That way, the numerical score underlying a particular risk rating (e.g., Moderate or 'M') is the same regardless of which cell along the diagonal of the matrix it is assigned to. The values associated with each category of volume score and consequence within the FRAT matrix do not span even orders of magnitude, but were assigned based on a review of the distribution of scores that were determined in a relatively small number of test cases. It is especially difficult to select the appropriate numerical

boundaries for the consequence score which, although assigned using numerical values, is essentially a qualitative parameter. This is something that should be carefully reviewed (and potentially adjusted) if a decision is made to continue advancing the FRAT.

A semi-quantitative approach could have been used to assign a numerical risk score by simply multiplying the volume and consequence scores together, but the qualitative risk matrix provides more flexibility in how the numerical boundaries between each category of volume and consequence score are assigned. It also has the advantage of more readily communicating the relative contribution of the volume and the consequence score to the total risk rating.

RATIONALE FOR THE SELECTION AND WEIGHTING OF GEOPHYSICAL ATTRIBUTES

This section of the report describes some of the options available for estimating sedimentation hazard potential (i.e., the likelihood of a geophysical process such as a landslide occurring and causing a certain volume of sediment to enter a stream), and an overview of the methods used in the FRAT. A rationale for the selection and weighting of the geophysical attributes used in the FRAT is provided and the algorithms and attributes are described.

METHODS FOR ESTIMATING SEDIMENT HAZARD POTENTIAL

Several methods are potentially available to estimate the sedimentation hazard potential from each of the hazards and scenarios considered in the FRAT. These include:

- Numerical methods based on first principles.
- Empirical models and weights of evidence methods based on statistical data.
- Semi-quantitative methods that make use of professional judgement and analysis using select application of the other methods listed above.

An example of a numerical method based on first principles is a slope stability factor of safety calculation. In slope stability analysis, the factor of safety is the ratio of the available shear strength to resist sliding divided by the shear strength required to maintain a state of equilibrium. A landslide will occur if the factor of safety falls below 1.0. To determine the factor of safety, several pieces of information are required including accurate estimates of:

- The slope height and inclination.
- The mechanism of slope movement and the geometry of the potential failure surface.
- The stratigraphy of the soil and/or bedrock making up the slope.
- The shear strength parameters (cohesion and internal angle of friction) within each stratigraphic unit, which are heavily dependent upon the soil and bedrock type, mineralogy, and density; the presence and orientation of pre-existing planes of weakness such as bedding, joints, and faults; and the history of prior movement within the slope.
- The groundwater pore pressures acting on the potential failure surface.

In a permafrost environment, the stability of a slope is further influenced by ground ice content and temperature.

Many of the parameters listed above can vary over time at the location of a potential pipeline watercourse crossing, either naturally (e.g., by bank erosion at the toe of the slope, changes

caused by forest fires, and climate change) or during pipeline construction (such as removal or change in the vegetative cover and grading of slope).

Most of the parameters identified above can only be determined with sufficient accuracy to facilitate slope stability calculations through detailed surface and subsurface geotechnical investigations (e.g., airphoto interpretation, surface mapping, topographic and bathymetric surveying, geophysical surveying, test pitting, drilling and monitoring of instrumentation), and even then uncertainty will be present. In theory, statistical or time-dependent distributions of values can be assigned to each parameter, allowing for a probabilistic assessment of the likelihood that the factor of safety will fall below 1.0 for different failure volumes and mechanisms. In practice this is rarely practical except at sites where very intensive investigations have been undertaken and where a long record of baseline conditions is available.

At most pipeline projects almost none of this information will be available at the time of permitting at the level of detail required for the vast majority of the proposed watercourse crossings due to constraints associated with site access, project schedule, and budget.

Empirical methods can be used to overcome some of the limitations associated with the (often) poor availability of detailed information required for slope stability analysis. Empirical methods can predict the likelihood of a landslide occurring at some point in the future based on statistical correlation with observable parameters in similar environments. Insights gained from first principles can provide an indication of the types of parameters that might prove most useful to include in the empirical models. For predictions of landslide frequency and volume, a detailed landslide inventory will be required, and site parameters such as slope height and inclination, geology, groundwater conditions and active processes must be known or reliably inferred. Weights of evidence can be used to assign the conditional probability of a landslide being present or occurring in the future given the presence or absence of each of these parameters.

Similar to methods based on first principles, the empirical methods tend to suffer from limitations in the data required to make statistically meaningful inferences. Modern and emerging technologies, such as light detection and ranging (LiDAR), are improving our ability to develop detailed inventories of landslides and some key parameters such as slope height and inclination. However, rarely are sufficient data available to assign correlations with other important parameters such as groundwater conditions and the presence and characteristics of pre-existing planes of weakness within the soil or bedrock. The changes in site conditions arising from pipeline construction activities, such as site grading, and implications for slope stability and erosion potential, are even more difficult to capture in a statistical model.

For the reasons outlined above, BGC elected to use semi-quantitative methods to assign the Annual Sediment Volume Score in the FRAT. The approach taken was to identify key attributes influencing the potential volume of sediment mobilized through the different hazard types and to assign numerical values to these attributes in a way that they could be used to calculate a relative 'score'.

OVERVIEW OF THE SEMI-QUANTITATIVE SEDIMENTATION HAZARD ALGORITHMS

Sedimentation hazard algorithms were developed to provide a relative ranking of the volume of sediment mobilized as a result of bank erosion, shallow landslides, surface erosion, loss of graded spoil material, and trenching activities, both in-stream and on the approach slopes. Algorithms were also developed to estimate the spatial probability (P(S:H)) that mobilized sediment from each crossing segment will reach the nearest stream.

The first step in estimating the potential for stream sedimentation at each stream crossing was to subdivide each crossing into segments with relatively uniform characteristics such as slope angle, surficial geology, and proximity to the stream.

A summary of the sediment hazards applicable to the various segment types during the baseline, construction, and operating scenarios is provided in Table 4.

Table 4. Applicable Hazards for Crossings Segments (Slopes, Banks, and Channel)

Scenario & Hazard	Bank Erosion*	Shallow Landslides	Surface Erosion	Grading Spoil**	Trenching Spoil**
Baseline	Banks (PS:H=1)	Slopes Banks	Slopes Banks	N/A	N/A
Construction	Banks (PS:H=1)	Slopes Banks	Slopes Banks	Slopes Banks	Slopes Banks Channel
Operation	Banks (PS:H=1)	Slopes Banks	Slopes Banks	N/A	N/A

Notes: Slopes = approach slopes from top of approach slope to top of bank
Banks = stream banks from top of bank to toe of bank
Channel = active stream channel between banks
*Spatial Probability (PS:H) assumed to be 1.0 for sediment derived from bank erosion
**Spatial Probability (PS:H) derived as a function of spoil storage location, and not necessarily the segment location

For each scenario (baseline, construction, and operation) the estimated annual sediment volumes (V) for the applicable hazards are summed and multiplied by the spatial probability to arrive at a total annual sediment volume contribution to the watercourse from each stream crossing segment.

The annual sediment volume from a particular hazard type is estimated by multiplying the estimated annual likelihood of the hazard occurring by the estimated volume associated with that hazard type. In most cases, the hazard likelihoods are estimated by multiplying the weightings assigned to each of the attributes that are relevant to the hazard type and local conditions present within each segment. For example, if it was determined that the likelihood of a certain hazard occurring was best estimated using three attributes (A, B and C), and the respective attribute scores for the particular crossing and segment in question were 1.0, 0.2 and 0.5, respectively, the associated likelihood score for that segment would be 1.0 * 0.2 * 0.5 = 0.1.

The individual sediment volumes that are mobilized and reach the stream for segments 1 through 'n' are summed to arrive at a total estimate for each crossing (Equation 2).

[2] $$Volume\_Score = \sum_{seg=1}^{n} V_{Bank} + (V_{Slide} + V_{Erosion} + V_{Trenching}) * PS:H + V_{GradeSpoil} * PS:Hgrading$$

This total Volume Score is used to populate the vertical axis of the qualitative risk matrix, as was illustrated in Table 1.

SELECTION OF ATTRIBUTES FOR ESTIMATING THE SEDIMENT HAZARD POTENTIAL

Attributes for use in the sediment hazard algorithms were selected based on literature review and the judgement of subject matter experts. The following objectives and criteria were used when selecting the key attributes:

- For efficiency of the data acquisition and rating process, minimize the number of attributes used – typically four to six key attributes are used to assign a numerical score to each hazard type.
- Focus on data that are likely to be available for all proposed stream crossings where permit applications are to be submitted (e.g., gathered from aerial photographs, topographic maps, regional geology maps, brief visual site inspections, and baseline geotechnical, hydrotechnical and environmental surveys, the Environmental Impact Statement, and the stream crossing application itself).
- Where possible, select attributes that are applicable to more than one hazard type.
- Where possible, use industry standard classification criteria and descriptions of pipeline construction and mitigation measures to develop the attributes (e.g., Mollard 1973; Selby 1985; Howes and Kenk 1997; CAPP 2005).
- Use attributes that capture the significance and influence of northern conditions, and in particular, ground ice content, on sediment mobilization potential, yet that still yield meaningful results when the methodology is applied in a non-permafrost environment (e.g., NRCan 1980-1985; Wall et al. 2002).

Many of the attributes selected for inclusion in the sediment hazard algorithms have also been utilized in other pipeline, railway, and urban landslide hazard and risk assessment methodologies that have been successfully applied in Canada and Internationally (Savigny et al. 2002; Esford et al. 2004; Muhlbauer 2004; Porter et al. 2005; Porter et al. 2007).

Details of the rationale for the selection of specific attributes and numerical weightings for each hazard type are documented in detail in a draft user manual prepared for AANDC in 2010: a brief summary of the process used to assign the numerical weightings is provided below.

SELECTION OF UPPER AND LOWER BOUNDS FOR SEDIMENT HAZARD ALGORITHMS

Professional judgement of subject matter experts was used to assign limits to the range of possible sediment hazard likelihoods and volume scores predicted by the various sediment hazard algorithms. For example:

- The annual average rate of bank erosion was assigned bounds between 1 mm/yr and 1 m/yr as this range is expected to be representative of the vast majority of natural and pipeline stream crossings.
- Local rates of shallow landslides on slopes steeper than 3 degrees were assumed to range from 0.01 to 100 times the average regional rate as estimated from aerial photography and landslide mapping.
- The percentage loss of spoil material generated during grading and trenching activities was assumed to range between 1 and 100%.

Establishing these upper and lower bounds was the first step in assigning numerical scores to the key attributes used for each hazard algorithm.

SELECTION OF NUMERICAL SCORES FOR ATTRIBUTES

The next step was to determine how much influence each of the key attributes should have on the hazard ratings. The most influential attributes were assigned a larger range of possible numerical scores. For example, all else being equal, the slope angle for segments inclined 3 degrees or more was expected to significantly influence the likelihood of shallow landslides and was assigned a relatively large range of possible scores (e.g., 0.4 to 4.0, or ranging by a factor of 10). In contrast, site drainage conditions (e.g., well drained versus poorly drained) which, although also important, was assumed by the subject matter experts to not exert as much influence as slope angle on the likelihood of shallow landslides, and was assigned a lower range of possible scores (e.g., 0.8 to 1.25).

Once the range of possible scores for each of the attribute types was defined, a check was made to ensure that the maximum and minimum possible scores that could be obtained by the hazard algorithm that used those attributes matched the pre-determined ranges that had been selected for that hazard type. Where necessary, adjustments to the maximum and minimum attribute score values were made until these criteria were met.

The next step was to rank the attribute classification list from worst to best for each of the applicable hazard types. Once relative ranking was complete, numerical scores were assigned within the pre-determined range for each attribute type. For example, for the purpose of estimating the potential for shallow landslides, the following numerical scores were assigned to different slope categories:

- Very Gentle (4 to 7 degrees (6-12%)) = 0.4
- Gentle (8 to 15 degrees (13-26%)) = 0.6
- Moderate (16 to 26 degrees (27-49%)) = 1.0
- Moderately Steep (27 to 35 degrees (50-70%)) = 2.5
- Steep (>35 degrees (>70%)) = 4.0

All else being equal, the algorithm used to estimate the annual likelihood of a shallow landslide would yield a landslide likelihood for a slope segment with Very Gentle slopes that was 10 times less than for a slope segment with Steep slopes.

MODEL ACCURACY

The relative influence of the various key attributes and the numerical scores used in the FRAT were assigned subjectively based on the experience and professional judgement of BGC's subject matter experts. Additional peer review was undertaken in a 2009 meeting of government and industry subject matter experts.

Although review was undertaken by BGC and subject matter experts to confirm that the sediment hazard algorithms yielded reasonable results when applied to a range of real streams and hypothetical pipeline stream crossings along the proposed Mackenzie Gas Project, it is very difficult to estimate the accuracy of the models.

While the characterization of the attributes used on the sediment hazard algorithms can be determined with reasonable consistency and accuracy, data necessary to calibrate the stream sedimentation algorithms and attribute scores used to estimate sedimentation volume are not available. Consequently, the sediment volume estimates are not expected to be precise. For these reasons, and as indicated earlier, the volume estimates are intended to be used as a basis for relative ranking only.

Accuracy cannot be estimated until the algorithms are applied at field sites where detailed measurements of sediment volumes can be obtained under natural conditions, and during and following pipeline construction. This is a weakness that will apply to any empirical or semi-quantitative predictive model.

OPPORTUNITIES FOR IMPROVEMENT OF THE FRAT

Four areas of potential improvement of the FRAT are identified and briefly described below:

- Simplification of the FRAT algorithms by removal of sediment hazard types and/or attributes that are deemed to be of lower significance.
- Further examination of sediment hazard and fisheries consequence attributes and relative weightings by independent subject matter experts.
- Field verification and collection of stream sedimentation process and volume data to aid in model calibration, as well as data collection to help validate the consequence model.
- Use of new and emerging technologies to improve the efficiency and accuracy of data collection, and potentially to enable the use of more traditional empirical methods to estimate sediment hazard frequency and volume for some hazard types.

The FRAT currently considers five sedimentation hazard types (shallow landslides, bank erosion, surface erosion, grading spoil loss, and trenching spoil loss) and three scenarios (baseline conditions, construction, and operation).

Potential sediment contributions from grading spoil loss and trenching spoil loss typically dominate the predicted sedimentation volume estimates during construction, and tend to be higher than the sedimentation volume estimates from landslides, surface erosion and bank erosion under baseline conditions or during operations. Sedimentation volume estimates from bank erosion are typically less under pipeline operating conditions than under baseline conditions because of the bank restoration techniques that are typically employed following pipeline construction. The potential for landslides and surface erosion could be higher or lower following construction, depending on the construction and site restoration techniques used, and the local geotechnical conditions.

The FRAT might be simplified by eliminating the bank erosion hazard scenario, and/or by only considering the construction scenario and potential sediment losses from site grading and trenching activities. These could reduce the number of attributes and algorithms required, and perhaps not significantly change the overall relative ranking of stream crossings.

The following models could be developed to address weaknesses of the fisheries component using a combination of existing Geographic Information Systems (GIS) and biological data, and new data gathered from the field:

- Species distribution models, especially for most sensitive fishes, to improve understanding of spatial and temporal (annual) distribution.
- Occupancy models to assign a probability of a particular species being present at any given stream crossing.

Improvement in the reliability of, and confidence in, the FRAT algorithms could potentially be achieved through further examination of sediment hazard and fisheries consequence attributes and their subjective numerical weightings by additional subject matter experts. This might be conducted through a series of workshops during which each hazard type, attribute, and numerical weighting is discussed in detail by a panel of subject matter experts from local

industry and government agencies. We suspect this would be a lengthy and costly exercise, but could result in more robust models and a greater confidence in the FRAT. While it may be difficult to achieve full consensus on attribute weighting within the hazard and consequence models, consensus on the minimum essential attributes used in the model and their relative significance should be achievable.

The FRAT could benefit from several significant advancements that have been made in the areas of data acquisition technology and the availability of regional digital datasets that can be manipulated using GIS. These offer opportunities for both more cost-effective acquisitions of data for model calibration, and for more accurate and efficient assignment of site attributes at stream crossings.

For example, very high-resolution ground elevation data acquired by LiDAR are now routinely acquired relatively early in the pipeline project lifecycle as part of pipeline routing and design activities.

The digital elevation models derived from LiDAR can be readily used to accurately estimate stream crossing geometries for a large number of crossings for much lower costs than through traditional terrestrial topographic surveys. Evidence of historical or active geomorphic processes such as landslides, surface erosion, bank erosion, and stream channel migration can be detected more accurately and efficiently than from traditional methods such as airphoto interpretation. Therefore, there are opportunities to improve the accuracy and efficiency of assigning stream crossing segment parameters such as slope angle, length, hazard type, and hazard activity.

Repeat LiDAR surveys and photogrammetric techniques can be used to detect changes in ground elevation over time and could be used to estimate locations and volumes of soil loss (and gain). Ground-based and un-manned aerial vehicle (UAV) LiDAR and photograph acquisition techniques are beginning to reduce costs, making it practical to carry out repeat surveys. Advances in LiDAR and photogrammetry technology may provide an opportunity to measure sediment volumes lost through processes such as bank erosion and shallow landslides under natural conditions and following pipeline construction at select test crossings. This could provide very valuable data for model calibration.

Digital datasets for stream networks are now available for most parts of North America, and historical and recent stream gauge data are now readily available on-line. This provides opportunities to quickly estimate stream hydrology at any location for a range of flood event return periods using databases and GIS.

Flood hydrology predictions, combined with knowledge of channel geometry and bed and bank materials, make it possible to estimate the potential for processes such as scour and bank erosion using empirical methods. Such methods have been used for decades by the pipeline industry, but typically at only a small percentage of proposed pipeline crossings because of the effort required to estimate flood flows and channel geometry. With the improved availability of digital stream networks, stream gauge data, and GIS capabilities, it is becoming practical to apply empirical methods at all existing or proposed pipeline crossings. Consequently, it might soon be practical to use empirical methods to replace or supplement the semi-quantitative methods of predicting soil loss from some sedimentation hazard types.

CONCLUSION

The FRAT is a tool to provide a relative ranking of stream sedimentation hazard and fisheries consequence from sedimentation that are combined using a risk matrix. The main objective of the FRAT was to facilitate a prioritization of pipeline stream crossing applications according to

an overall risk rating, thereby providing an objective means for allocating review effort and improving the timely review of development applications. Additionally, it was believed that the FRAT could facilitate the storage and retrieval of relevant terrain, watercourse and fisheries data for each proposed pipeline crossing, improve communication between DFO and pipeline proponents, and encourage the use of best practices for pipeline routing, design, construction, and operation. While the focus of the FRAT was the Mackenzie Gas Project, it was hoped that ultimately a version of the FRAT could be applied across Canada to streamline DFO's regulatory process for other pipeline watercourse crossings.

The geomorphic and pipeline-construction processes with the potential to contribute to stream sedimentation are extremely complex, and there are currently insufficient data to select and weight model attributes using statistical methods. Consequently, the FRAT uses semi-quantitative methods derived from the experience and judgement of subject matter experts. Given the same assignment, a different set of subject matter experts would almost certainly come up with different attribute weightings that might yield different results. However, it is essential that the subject matter experts agree on which are the most critical attributes that should be included in the hazard and consequence model, and how they should be assigned in a systematic and repeatable way. This should be one of the key objectives of any further review of the FRAT.

Further review of the FRAT algorithms, combined with technological advances in data collection and analysis could improve the ability of the FRAT to predict stream sedimentation hazards, but the challenges outlined above will persist until the tool (or another version of it) is applied at a large number of pipeline stream crossings where monitoring and survey data are available to improve model design and calibration over time.

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